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# *Residential ICT related energy consumption which is not registered at the electric meters in the residences*

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## *Background*

The development of the ICT hardware has resulted in products with rapidly increasing functionality and capacity providing the users with a whole new range of possible applications. Due to the product development the energy consumption measured per functional unit has decreased. However the functional unit of each product is constantly expanding as the increased capacity opens up to new applications. E.g. 15 to 20 years ago an average pc was merely an advanced typewriter / calculator. Today the average residential pc is still named “a pc”, though the increased functionality also has made it a video machine, a stereo equipment, a radio, a TV, a communication device (email, fax, (video-) phone etc.), a toy, a photo album, a photo laboratory, a library etc. This development leads to new use patterns that inevitably imply an increased electricity consumption.

The main focus of the project *“Behavioural and technical potentials for energy conscious development of residential ICT applications”* is on the electricity consumption, which is related to the application of ICT in the households. This means the electricity consumption that is caused by the ICT equipment in the form of computers, screens, printers, routers etc. This electricity consumption is easy to read from the electric meter connected to the residence. However there are other causes to energy consumption, which can be directly related to the use of ICT in the households as it is outlined in figure 1.

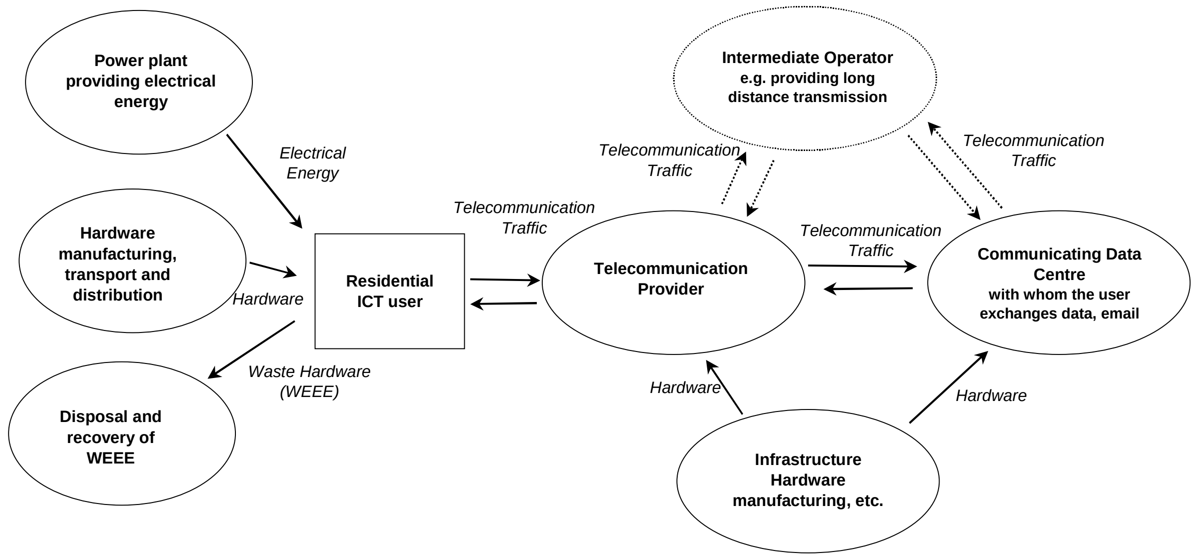


***Figure 1** Outline of residential energy consumption*

One aspect derived from the residential ICT activities is the energy consumption related to the manufacturing (including raw material extraction), transport (over the entire life cycle) and disposal of the ICT equipment.
Another aspect of the application of residential ICT is the integration of the Internet and other telecommunication, which has expanded and gained increasing importance over the last decade. The operation of this infrastructure also gives rise to energy consumption. When the residential ICT user is communicating with “the cyberspace” this communication requires energy consumption.

This communication is performed through a telecommunication provider, who supplies access to the Internet, email, web-hotel, cable TV, telephony etc. This telecommunication provider operates a number of servers, switchboards, networks and other energy consuming hardware. Through the telecommunication provider the user can carry out the communication with other servers exchanging data, email, telephony etc. – named the “Communicating data centre” in figure 1. The operation of servers, server-room air-conditioning and other equipment at the data centres also requires energy. In some cases the telecommunication provider would direct your traffic through another (intermediate) telecommunication provider e.g. to connect to overseas servers through optical fibre cables. Finally the manufacturing of infrastructure hardware requires energy.
This energy consumption that takes place outside the residence will be dealt with in more detail in the following sections.

## *Purpose*

The purpose of this paper is to perform a literature study in order to uncover the energy consumption related to the application of residential ICT, but which does not appear on the electric meters in the households. This is:

- The energy consumption related to the manufacturing, transport and disposal of the residential ICT equipment.
- The energy consumption related to the ICT infrastructure related to residential ICT application.

## *Primary Energy*

To be able to compare the energy consumption in the use phase with the other phases of the life cycle it is necessary to convert the different sorts of energy consumption to the same unit being primary energy measured in MJ (Mega Joule). This is an aggregation of the total life cycle energy and it is the sum of the 'Net Calorific Value' (Material Energy) and the energy used for manufacturing (process energy). As primary energy is a key issue of this paper it might be worthwhile to assign a few words to this subject.

All materials need energy to be produced. This processing energy - needed for extraction, refining and further processing of virgin resources into 'ready-to-use' materials - will typically be electrical or thermal. Some materials like plastics are synthesised from energy sources like gas or oil and thereby have an inherent energy content.

The total energy input to a material is the sum of processing and inherent energy. In order to add these energies, a common unit - primary energy - is needed. Primary energy is the combustion values of the fuels used to generate the processing energy or the combustion value of the gas or oil applied for e.g. plastics synthesis. This implies that e.g. electrical energy has to be multiplied by a factor corresponding reciprocally to the efficiency of the electricity generation system. This factor is typically in the order of two to three.
Some of the inherent energy in plastics may be recovered by incineration. This energy corresponds to the combustion value of the material. It should be remembered that this energy cannot be recovered to 100%, and it has to be corrected by the efficiency of the incineration system. The Primary energy consumption is also referred to as “Gross Energy Requirements” [99].

In this context the conversion factor 9 MJ/kWh [101] is applied in case there is a need to convert electrical energy to primary energy. This factor is derived from two conversion factors:

- 3,6 MJ electrical energy / kWh electrical energy, and
- 2,5 MJ primary energy / MJ electrical energy

The last factor expresses that a total of 2,5 MJ of energy has been consumed to be able to supply 1 MJ of electrical energy at the power outlet. Some of the energy consumption referred to in the following also cover heating and fuel for transport. The same conversion factor is used to calculate the primary energy consumption for these categories of energy consumption. The error this may introduce is considered to be insignificant as electricity consumption is the dominating energy category.
In the following sections a number of values of primary energy consumption will be presented and discussed. For comparison it could be mentioned that the average electricity consumption in a detached house in Denmark occupied by a family of 4 persons, would be approx. 5.000 kWh/year [7], which corresponds to 45.000 MJ primary energy per year.

## *Energy consumption for manufacturing, transport and disposal*

The primary energy consumption related to the manufacturing (including extraction of raw material), transport and disposal of desktop PCs is presented in table 1. The values from ref. 1, 39 and 80 are based on genuine LCAs (life cycle assessment) while the values from ref. 18 and 19 are based on screening methodology. This might to some extent explain the differences though the time of the data generation and variations in the analysed equipment are also assumed to be important.

| Equipment | Energy Consumption [MJ / Unit] | Year data | Reference |
|---|---|---|---|
| Control Unit | 5.597 | 2001 | Loerincik [1] |
| Chips and Microchips | 3.750 | 2001 | Loerincik [1] |
| PWB | 1.399 | 2001 | Loerincik [1] |
| Bulk Materials | 448 | 2001 | Loerincik [1] |
| Control Unit | 1.930 | 2003 or earlier | Plepys [10] |
| Control Unit | 2.594 | 2005 | Jönbrink [18] |
| Control Unit | 3.900 | 2000 | Legarth & Willum [19] |
| Control Unit & 17" CRT screen | 5.040 | 1998-2001 | Kuehr & Williams [39] |
| Control Unit & 15" CRT screen | 3.544 | 1998 or earlier | Atlantic Consulting and IPU [80] |

***Table 1** Energy Consumption for the manufacturing, transport and disposal of desktop computers. Applied abbreviations: PWB: Printed Wired Board, CRT: Cathode Ray Tube.*

Values from ref. 1 are divided up in groups of components and it is demonstrated that the manufacturing of chips and microchips (semiconductors) is contributing heavily to the energy consumption. If you examine the results from the other studies you will uncover a similar pattern. The increasing improvement of the semiconductors´ functionality implies the utilization of chemicals and materials of an ever-increasing purity in the manufacturing processes. Plepys [10] claims that the energy consumption caused by this extreme purification is very energy-intensive and

that this is not taken into account by performing the respective LCAs. If you accept this reasonable argumentation the values represented in this context should be considered to be lower to than “true values”.
The energy consumption in the life cycle (except the use phase) of an ICT product is mainly caused by the manufacturing and transport. The disposal phase will usually only contribute marginally to the energy balance. If the waste ICT equipment is disposed of in accordance with the WEEE directive [102] energy recovery might reduce the total energy consumption by a few percent. Some of the referred studies do not include the disposal phase and this is a reasonable approximation if you consider energy consumption. (If you would also consider the depletion of scarce resources like copper, silver, platinum etc. this approximation would not be justified.)
The primary energy consumption for the manufacturing etc. of PC screens is presented in table 2.

| Equipment | Primary Energy Consumption [MJ / Unit] | Year data | Reference |
|---|---|---|---|
| CRT Screen, Size not specified | 1.445 | 2001 | Loerincik [1] |
| LCD Screen, Size not specified | 653 | 2001 | Loerincik [1] |
| CRT Screen 17" | 1.410 | 2005 | Jönbrink [18] |
| LCD Screen 17" | 1.225 | 2005 | Jönbrink [18] |
| CRT Screen 15" | 979 | 2000 | Legarth & Willum [19] |
| TFT Screen 15" | 5.940 | 2000 | Legarth & Willum [19] |
| TFT Screen 17" | 7.850 | 2000 | Legarth & Willum [19] |
| CRT Screen 17" | 18.538 | 2001 | Socolof [91] |
| TFT Screen 15" | 1.989 | 2001 | Socolof [91] |

***Table 2*** *Energy Consumption for the manufacturing, transport and disposal of pc screens. Applied abbreviations: CRT: Cathode Ray Tube, LCD: Liquid Crystal Display, TFT: Thin Film Transistor. (LCD and TFT are both flat screens).*

These values are together covering a wide range. The values from ref. 18 and 19 are based on screening methodology, while ref. 1 and 91 are real LCAs. Especially the LCA performed by Socolof [91] seems to be a very thorough and comprehensive study, and several ICT manufacturers were involved. The energy consumption for manufacturing of a 17” CRT screen calculated by Socolof [91] is radically different from the results obtained by the other authors. As CRT screen are being phased out [98] the reason for this difference will not be dealt with any further.
The primary energy consumption for the manufacturing etc. of PC laptops is shown in table 3.

| Equipment | Primary Energy Consumption [MJ / Unit] | Year data | Reference |
|---|---|---|---|
| Laptop | 3.710 | 2001 | Loerincik [1] |
| Chips and Microchips | 2.300 | 2001 | Loerincik [1] |
| PWB | 408 | 2001 | Loerincik [1] |
| Bulk Materials | 1.002 | 2001 | Loerincik [1] |
| Laptop with 15" LCD | 1.368 | 2005 | Jönbrink [18] |
| Laptop with 14" TFT LCD | 1.868 | Publ. 2005 | Oikawa [51] |

***Table 3 Energy** Consumption for the manufacturing, transport and disposal of laptops. Applied abbreviations: PWB: Printed Wired Board, LCD: Liquid Crystal Display, TFT: Thin Film Transistor.*

Compared to the desktop PCs the energy consumption to manufacture laptops appears to be lower. This conclusion is supported by the two authors Loerincik [1] an Jönbrink [18], who both have compared desktop and laptop PCs within the same study. It is somewhat surprising that the manufacturing of laptops implies less energy consumption bearing in mind that the manufacturing of semiconductors is an important contribution. Furthermore it should be expected that a product being more compact and complex would imply increased energy consumption. This might be explained by the circumstance that the same basic inventory data for materials and components are used no matter whether it is a desktop PC or a laptop. At least this is the case for the VHK-tool [99] applied by Jönbrink [18]. It would be reasonable to expect that in the reality the materials and components for laptops would require more energy for the manufacturing processes.

In table 4 the energy consumption related to the manufacturing, transport and disposal of printers and multi functional devices (MFD) is presented. The values cover a wide range, which can be explained from diversity in functionality and capabilities.

| Equipment | Primary Energy Consumption [MJ/Unit] | Year data | Reference |
|---|---|---|---|
| Printer, average weight 20 kg | 11.540 | 2001 | Loerincik [1] |
| EP-Copier MFD, monochrome, Basic workgroup | 7.369 | 2005 | Stobbe [44] |
| EP-Copier MFD, colour, Advanced workgroup | 14.639 | 2005 | Stobbe [44] |
| EP-Printer SFD, monochrome, Standard Laser Printer | 2.861 | 2005 | Stobbe [44] |
| EP-Printer SFD, colour, Advanced Laser Printer | 4.973 | 2005 | Stobbe [44] |
| IJ-Printer MFD, personal | 1.528 | 2005 | Stobbe [44] |

***Table 4** Energy Consumption for the manufacturing, transport and disposal of printers and related equipment. Applied abbreviations: EP: Electro Photography; IJ: Ink Jet; MFD: Multi Functional Device; SFD: Single Functional Device.*

The values from the tables 1 to 4 are presented graphically in figure 2.

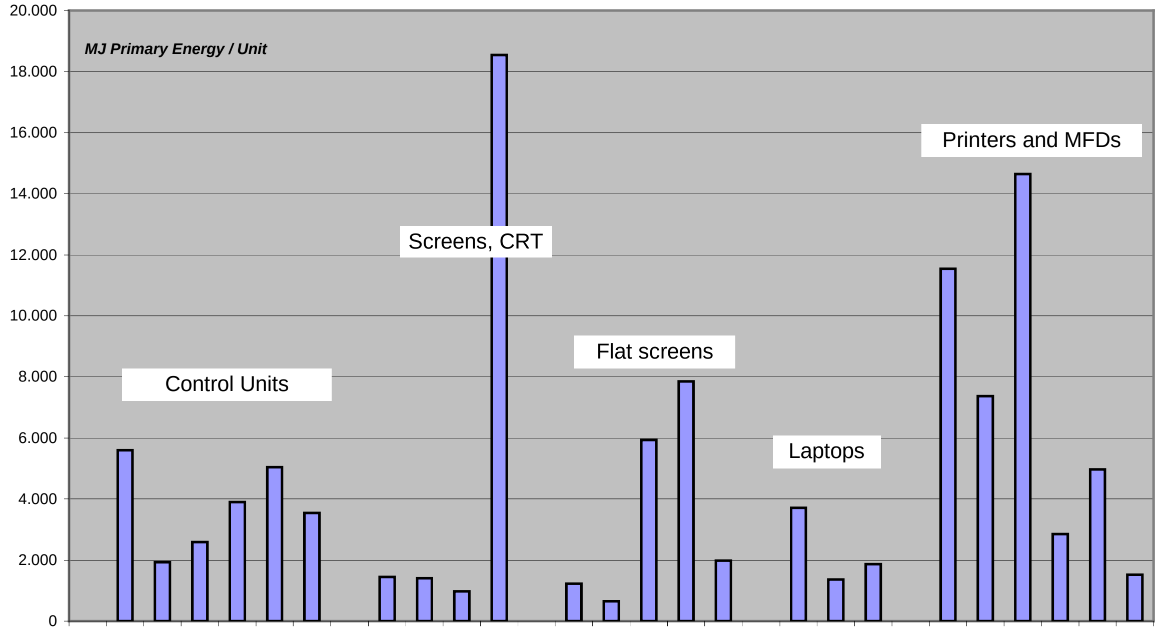


***Figure 2*** *Primary Energy Consumption [MJ/Unit] for the manufacturing, transport and disposal of desktop PCs, screens, laptops, printers and MFDs. Applied abbreviations: CRT: Cathode Ray Tube, MFD: Multi Functional Device.*

The manufacturing of smaller ICT devices also consumes considerable amounts of energy. The manufacturing of a PDA requires 499 MJ primary energy [20] and for a cellular phone it is 111 MJ primary energy [27].
It can be quite difficult to relate all these values to something more substantial. In the previous section the average electricity consumption corresponding to 45.000 MJ primary energy per year for an average family was mentioned as a value for comparison.
Another way to approach these figures is to compare the primary energy consumption in the use phase to the total primary energy consumption related to the manufacturing, transport and disposal for the respective products. This is done for those of the above-mentioned studies that have considered the use phase. The results are shown in table 5. Values for other products and more general statements have been added for comparison.

| Compared item | Use / Manufacturing | Reference | Year |
|---|---|---|---|
| Desktop computer | 0,3 | Kuehr & Williams [39] | 1998-2001 |
| Refrigerator | 8,0 | Kuehr & Williams [39] | 1998-2001 |
| Most appliances | >1 | Kuehr & Williams [39] | 1998-2001 |
| CRT screeen, 17" | 0,1 | Socolof [91] | 2001 |
| LCD screeen, 15" | 0,4 | Socolof [91] | 2001 |
| Desktop computer (Control Unit & 15" CRT) | 2,9 | Atlantic Consulting and IPU [80] | 1998 or earlier |
| Home Desktop PC | 3,8 | Jönbrink [18] | 2005 |
| Laptop at home | 2,7 | Jönbrink [18] | 2005 |
| LCD at home | 2,7 | Jönbrink [18] | 2005 |
| CRT at home | 5,0 | Jönbrink [18] | 2005 |
| ICT equipment | 1-6 | Stevels [97] | 2004 |
| Printer excl. paper | 0,5 - 6 | Stobbe [44] | 2005 |
| Printer incl. paper | 1 - 62 | Stobbe [44] | 2005 |
| PDA | 0,42 | Toffel [20] | 2004 |
| Cellular Phone, UMTS | 0,07 | Emmenegger [6] | Publ. 2006 |

***Table 5*** *The ratio of the primary energy consumption in the use phase vs. the primary energy consumption related to the other phases of the life cycle (manufacturing, transport and disposal) for various ICT equipment. Applied abbreviations: CRT: Cathode Ray Tube, LCD: Liquid Crystal Display, PDA: Personal Digital Assistant, UMTS: Universal Mobile Telephone System (3G).*

These ratios also cover a wide range of values. While the energy consumption related to manufacturing etc. should be considered to have a “true value”, which you could be able to determine for a specific product, this is not the case for the use phase of the same ICT-product as it is dependent on the behaviour of each individual ICT user. The use phase models that have been applied in these studies are thus an average estimate.
One should therefore be very careful to interpret the figures in table 5, but it seems like newer studies estimate the use phase to be relatively more important than older studies when it concerns PCs and displays. When it comes to printers and copiers it can be seen that the use phase contribute heavily to the energy consumption – especially if paper consumption is included. For comparison it can be mentioned that a package containing 500 pieces of A4 paper requires 74 MJ of primary energy to be produced [1].
For the mobile devices (PDA and cellular phone) the use phase is estimated to be less important compared to manufacturing. This is especially striking for the cellular UMTS phone. One reason for this is that the average lifetime of a mobile phone is only one year and the manufacturing phase will thus be more dominating than e.g. for the PDA with lifetime of 3 years. The highly effective power management of the newer cellular phones is another cause. As the energy consumption is related to the battery lifetime, which is an important commercial parameter, this issue has attention in the development departments by the manufacturers. There is no specific data to calculate a ratio for the GSM phone, but the available data [6] indicate that the ratio would be somewhat higher compared to the UMTS phone.

## *Energy consumption related to the infrastructure*

The energy consumption related to the operation of the ICT infrastructure is a theme, which is only moderately illuminated, and the average residential ICT user probably does not spend many a wakeful night wondering about this issue.

Cremer et. al. 2003 [5] estimates the electricity consumption of telecommunication to be 6% of the ICT related electricity consumption in 2001 increasing to 11% in 2010. Other authors [49, 50 & 90] also support that the infrastructure is gaining increasing importance in terms of energy consumption.

The energy consumers in the ICT infrastructure are outlined in figure 1. The energy consumption of the telecommunication providers can be extracted from their respective environmental reporting [3, 81 and 85]. When they also report the amount of their telecommunication traffic it is possible to calculate the energy consumption in proportion to the performed telecommunication traffic. Such values are presented in table 6.

| Transmission / Source | Energy Consumption in kWh / GB | Energy Consumption in MJ primary energy / GB | Year data |
|---|---|---|---|
| Telecom traffic, Swisscom 2005 [82] | 10,7 | 96 | 2005 |
| Telecom traffic, Swisscom 2000 [82] | 30,3 | 273 | 2000 |
| Voice and data traffic in mobile and fixed networks, Telecom Italia 2006 [81] | 3,9 | 36 | 2006 |
| Voice and data traffic in mobile and fixed networks, Telecom Italia 2003 [81] | 17,5 | 157 | 2003 |
| Cable TV, Internet and telephony in mobile and fixed networks, TDC 2006 [3 and 95] | 1,4 | 13 | 2006 |
| Cable TV, Internet and telephony in mobile and fixed networks,TDC 2004 [3 and 95] | 1,7 | 15 | 2004 |
| Cellular - to cellular phone in the UMTS network [6] | 325 | 2.922 | Publ. 2006 |
| Cellular - to cellular phone in the GSM network [6] | 247 | 2.219 | Publ. 2006 |
| Digital Power Group. Creation, transfer and storage [50] | 3,9 | 35 | Publ. 2007 |

***Table 6*** *The primary energy consumption related to the operation of different ICT infrastructures. Applied abbreviations: UMTS: Universal Mobile Telephone System (3G), GSM: Global System for Mobile Communications.*

The values from the telecommunication operators are derived from their published environmental reporting. The energy consumption includes electricity as well as heating and fuels for transport. The values given in kWh/GB are directly derived from the references while the values expressed in MJ primary energy/GB are converted from these values by the factor 9 MJ/kWh [101] as discussed in the previous section about primary energy.

These figures cover a wide range, but it is a common trend for all three operators that the energy efficiency has improved over time. When you compare values covering the same (or almost the same) year the differences are not really that striking. Differences among the operators in terms of mix of voice, data, fixed or mobile traffic will probably be able to explain some the differences in energy efficiency. Only TDC [3] accounts for their mix in traffic, which is dominated by cable TV (82%) and Internet (14%).

Another reason for the differences could be the applied equipment. According to Moore's law [103] the density of transistors will double approximately every 18 month. This means that a new server unit will have an increased functionality, but still take up the same space in the server room. If the increased functionality would imply a corresponding increase in the energy consumption this would hamper a proper and reliable function of the hardware [108] and also imply a disproportionate increase in the demand for cooling capacity in the server rooms [95]. The result is thus that newer hardware will consume less energy compared to the performed functionality.

TDC does not state their telecommunication traffic as an amount of transmitted data. They state their performance as "Capacity pull" measured in kbps (kilo bits per second), which corresponds to the total amount of sold bandwidth. From TDC environmental reporting [3] it can be calculated that an average customer who has an Internet connection with a bandwidth of 1Mbit/s implies energy consumption by TDC of 66 kWh/year (595 MJ primary energy/year), which correspond to an average data volume of 47 GB/year. By comparing the capacity pull to the actual measured traffic in the TDC network [95] the ratio between the actual data traffic and the sold bandwidth can be calculated. It is thus possible to calculate the values in table 6 that are comparable to the values given by Swisscom and Telecom Italia.

When it comes to mobile telecommunication a distinct increase in the energy consumption is demonstrated. These values only cover electricity consumption related to operate the infrastructure. The lower energy efficiency in the UMTS network is due to a higher electricity consumption to operate the base stations compared to the GSM network. Emmenegger [6] has calculated the energy consumption including the manufacturing of hardware in the UMTS infrastructure to 5397 MJ primary energy/GB. This means that the energy consumption from the manufacturing of the infrastructure hardware is almost the same as the energy used to operate the mobile infrastructure. No such figures relating to the energy consumption for manufacturing of the infrastructure hardware were available from the telecommunication operators.

The last value in table 6 has been calculated from the statement: "Creation, storage and transmission of 10 MB data corresponds to the combustion of 1 kg of coal" [Digital Power Group taken from ref. 50]. Based on data from an average Danish coal-powered plant [88] the 10 MB data/kg coal has been converted to 3,9 kWh electricity consumption /GB data.

The energy consumption by the telecommunication provider has then been accounted for. The energy consumption at the telecommunication provider also covers the traffic to the residential ICT user, and approximately half of the traffic to/from the "Intermediate Operator" and the "Communicating data centre".

It has not been possible to find data about the energy consumption related to the data transmission between the Internet provider and other operators and data centres in the ICT infrastructure - e.g. through an optical fibre cable across the Atlantic Ocean. Several sources [95, 104 & 105] however estimate the energy consumption for the operation of the long distance fibre cables to be insignificant compared to the energy consumption required to operate the telecommunication operators network.

Returning to figure 1 the energy consumption initiated as a result of the communication with the "Communicating data centre" has to be accounted for. Koomey 2007 [4] has calculated that servers and related cooling and auxiliaries are responsible for 1,2% of the electricity consumption in the

USA in 2005, and the consumption is estimated to be 1,5 - 2,0% if data storage and networks are included. Since 2000 this energy consumption has increased by almost a factor two. Other authors also predict the energy consumption of data centres to increase considerably in the future [62 & 72]. Literature about the energy consumption of servers and data centres is rather comprehensive. But very few authors relate the energy consumption to performance in terms of the transmitted data traffic. Fujitsu-Siemens [106] state the electricity consumption for two of their servers as a function of the capability in terms of "throughput" in Mbit/s and the number of simultaneous users. From these data the electricity consumption can be calculated to be 0,0002 to 0,001 kWh/GB. This value only covers the electricity consumption to run the servers. There will also be an energy consumption to provide cooling to the server room. This energy consumption is estimated to be of the same size as the energy consumption to operate the servers [71]. Furthermore electricity consumption to operate data storage and networks has to be added. Koomey [4] estimates this to be 20 to 40% of the total energy consumption of a data centre.
It is thus possible to calculate an estimate for the energy consumption by the "Communicating data centre" to be 0,0006 to 0,004 kWh/GB transmitted.
In table 7 the estimate of the energy consumption related to transmitted data volume in the telecommunication infrastructure is presented.

| | **Energy Consumption in $10^{-3}$ kWh / GB** | **Energy Consumption in $10^{-3}$ MJ primary energy / GB** |
|---|---|---|
| Actual data transmission (mainly by fibre cables) | ~0 | ~0 |
| Communicating data centre, server | 0,2 - 1,2 | 2 - 11 |
| Communicating data centre, Cooling | 0,2 - 1,2 | 2 - 11 |
| Communicating data centre, data storage and networks | 0,1 - 1,7 | 1 - 15 |
| **Total** | 0,6 - 4 | 5- 37 |

***Table 7*** *Estimate of the energy consumption to operate the "Communicating data centres" in relation the transmitted data volume.*

Several sources [71, 95 &106] conclude that the energy consumption of the infrastructure hardware is almost independent of the current load, because the base functionalities are running uninterrupted no matter what the current load might be. In that sense there is no direct relation on a day to day to basis between the transmitted data and the energy consumption as it is indicated in table 7. There is a relation however seen over a little longer time span in the sense that an increased application of the Internet (e.g. downloading of movies and music) implies the installation of additional energy consuming hardware.

Left to account for in figure 1 is now the energy consumption related to the manufacturing, transport and disposal of the infrastructure hardware. As mentioned above only one study dealing with the infrastructure hardware has been identified. From this study [6] it can be calculated that the energy consumption related to the manufacturing etc. is almost the same as is required to operate the UMTS infrastructure. A rough estimate for the energy consumption needed to manufacture the infrastructure hardware can be derived by extrapolating the use / manufacturing ratio for other hardware (table 5). For a desktop PC the ratio can be calculated from Jönbrink [18] to be 5,2 for an office PC (and 3,8 for the same device used at home), and Stevels [95] estimate an interval from 1 to 5 for “electronic products”. Stevels does not explicitly state that it refers to consumer electronics, but it is assumed to be so from the context. Kuehr & Williams [39] estimate the ratio to be 0,3 for a desktop PC. The establishment of this figure is however not explained and no reference is given so this value is not given any priority. It is expected that the professional hardware applied to operate the ICT infrastructure is running more or less around the clock. It should thus be expected that the use / manufacturing ratio is considerably higher than for an office PC. It would be more relevant to compare to a high utilization EP-Printer [44] where the ratio can be calculated to 6,2 if paper consumption is excluded. But even such a printer would not have an operating frequency comparable to the infrastructure hardware. Based on these considerations the ratio of the energy consumption of the use phase vs. the energy consumption for the manufacturing etc. is estimated to be at least 12, and this value is applied to derive a conservative estimate for the energy consumption related to the manufacturing of the infrastructure hardware as it is presented later in table 8, well knowing this is an arbitrary choice.

## *Sensitivity Analysis*

The results derived above will be summed up in table 8 in the next section. But before doing this it is considered worthwhile to perform a sensitivity analysis to evaluate the reliability of the results and the assumptions that have to be made, and to what extent the conclusions may be influenced.
The energy consumption to manufacture residential hardware presented in tables 1 to 4 are considered to be robust within those differences that are shown. Beside the main ICT products (PC, screen, laptop and MFD) there is also ADSL modem. The energy consumption to manufacture this item is estimated to 133 MJ primary energy using the VHK Tool [99]. With the purpose of comparing the energy consumption for manufacturing the hardware to the energy consumption to operate the hardware a product lifetime has to be estimated. This is set to an average of 4 years based on previous considerations [19]. An increase in the lifetime will reduce the significance of the load from the manufacturing and vice versa. But even if a lifetime of 6 years is assumed the energy consumption related to the manufacturing will still be of the same size as the residential energy consumption.
An average bandwidth of 2,4 Mbit/s has been calculated on the basis of statistics for Demark [107]. This covers both residential and professional users and is thus not quite representative for an average residential customer. However with the increase in the availability of the bandwidth and the decrease in prices [107] it is expected that a bandwidth of 2,4 Mbit/s will be representative in the near future.
The energy consumption by the Internet provider (in table 8) is based on data from TDC [3 & 95], who is the market leader in Denmark. Other telecommunication providers [81 & 82] show values that are somewhat higher but still of the same size. The values based on TDC data are thus considered to be reliable.
As it appears from the previous (table 7) the energy consumption related to the “Communicating Data Centres” is not in the same way based on solid foundation. By the calculation of the energy consumption it is assumed that the energy needed to operate the hardware is equal to the energy needed to cool the server room [71]. This rule of thumb is considered to be rather conservative and it is expected that an increased focus on the energy consumption by the data centre operators would reduce the energy needed for cooling. The average presented in table 8 is thus considered to be conservative.
The manufacturing of the infrastructure hardware also implies energy consumption. This is derived from an estimate of 12 for the ratio of the energy consumption of the use phase vs. the energy

consumption for the manufacturing of the hardware, as reasoned about in the previous section. Though this energy consumption seems to be associated with sincere uncertainty. However even considerable deviations from the value stated in table 8 will not change the conclusion that the energy consumption related to the manufacture of the infrastructure hardware is of minor importance compared to the energy needed for the operation.
On the basis of the above considerations it can be concluded that the conclusions derived from this study in the next section are robust to any reasonable deviations in the applied data and assumptions.

## Conclusions

All the items outlined in figure 1 have thus been taken into consideration and an attempt to estimate the overall energy consumption related to residential ICT can be done. This is done for a typical Danish household assumed to have one desktop pc, one laptop, one MFD and one ADSL modem. The results are presented in table 8 below.

| | **MJ primary energy/year** | **kWh/year** | **kWh/year** |
|---|---|---|---|
| | | | **Totals** |
| **Residential Electricity consumption** of the hardware listed below based on [110] | 2.702 | 300 | **300** |
| | | | |
| Manufacturing of one PC, Control Unit | 876 | 97 | |
| Manufacturing of one Screen, LCD 17" | 811 | 90 | |
| Manufacturing of one Laptop | 579 | 64 | |
| Manufacturing of one Combined printer, scanner etc (MFD) for personal use | 382 | 42 | |
| Manufacturing of one ADSL Modem | 33 | 4 | |
| **Manufacturing of hardware used in the residence** | | | **298** |
| Internet provider (2,4 MBit/s) based on [3] and [95] | 1.417 | 157 | |
| Communicating Data Centre average | 2 | 0,3 | |
| Manufacturing of hardware used outside the residence | 118 | 13 | |
| **Energy consumption of the infrastructure taking place outside the residence** | | | **171** |

***Table 8*** *Estimate of the total energy consumption related to residential ICT and the integrated application of the Internet for a typical Danish household with ADSL-connection.*

The figures in table 8 are aiming at representing a typical Danish household. The figures are in values of primary energy in the unit MJ. As primary energy is probably somewhat awkward to many readers the values are converted to kWh bearing in mind that not all energy consumption is electricity consumption.

The figures presented in table 8 are based on the following assumptions:

Electricity consumption of the residential hardware listed below is based on [110].
Energy consumption to manufacture residential hardware are based on:

Control unit: Average values from [1, 10, 18 & 19].
LCD Screen, 17” : Average values from [1, 18 & 19].
Laptop: Average values from [1, 18 & 51].
MFD is represented by the Ink Jet MFD from [44], which is the product type with the highest penetration in Danish residences [110].
ADSL Modem is estimated from the content of a Cisco 677 by means of the VHK-Tool [99].

Lifetime of residential hardware: 4 years

| | |
|---|---|
| Average bandwidth of the users connection in 2007 estimated from [107] : | 2,4 Mbit/s |
| Transmitted data for 1 Mbit/s bandwidth connection in 2006 calculated from TDC data [3 & 95]: | 47 GB/year |
| Energy consumption to operate the “Communicating data centres” are average values calculated from table 7. | |
| Ratio use phase vs. energy consumption for manufacturing etc. of the infrastructure hardware: | 12 |

It is obvious from the previous section, that the values presented in table 8 are associated with considerable uncertainty and should thus merely be considered as an approach to estimate the order of magnitude of the energy consumption related to the increasing application of residential ICT and the related infrastructure.
It can however be concluded that the energy consumption, which does not appear on the electric meters in the households is significant and exceeds the electricity consumption which takes place within the residence. A rule of thumb based on the values in table 8 will be:

- When 1 kWh is consumed in the residence 1 kWh is consumed to manufacture, transport and dispose of the hardware and ½ kWh is consumed to run the Internet and the applied ICT infrastructure outside the residence.

For cellular phones the manufacturing phase is responsible for the major part of the energy consumption. The highly effective power management of the newer cellular phones combined with a very short product lifetime is the cause for this.

The most important energy consumption related to the application of office printers and copiers is caused by the use of paper. The energy consumption from the manufacturing of the paper exceeds the energy consumption for manufacturing of the hardware and the electricity consumption in the use phase several times.

The most essential energy consumption of the infrastructure is related to the Internet provider. The energy efficiency of the Internet provider’s infrastructure is however increasing. For one operator this has increased more than 100% per year [81]. This means that more data volume is transmitted compared the amount of energy consumed.

The application of the ICT infrastructure is increasing and so is the energy consumption related to this. The energy consumption of the infrastructure hardware is almost independent of the current load, because the base functionalities are running uninterrupted no matter what the current load might be. In that sense there is no direct relation on a day to day to basis between the transmitted data and the energy consumption. There is a relation however seen over a little longer time span in the sense that an increased application of the Internet (e.g. downloading of movies and music) implies the installation of additional energy consuming hardware.

The amounts of stored data have increased dramatically over the last years. Energy consumption to store and keep these amounts of data accessible might be more important in the future if this increase continues at the same rate.

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